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PROGRESS TOWARDS A NEW CANADIAN IRRADIATION-RESEARCH FACILITY

by

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AECL RESEARCH

1. INTRODUCTION

As reported at the second meeting of the International Group on Research Reactors, Atomic Energy of Canada Limited (AECL) is evaluating its options for future irradiation facilities [1]. During the past year significant progress has been made towards achieving consensus on the irradiation requirements for AECL's major research programs and interpreting those requirements in terms of desirable characteristics for experimental facilities in a research reactor. The next stage of the study involves identifying near-term and long-term options for irradiation-research facilities to meet the requirements. The near-term options include assessing the availability of the NRU reactor and the capabilities of existing research reactors. The long-term options include developing a new irradiation-research facility by adapting the technology base for the MAPLE-X10 reactor design [2]. Because materials testing in support of CANDU[1] power reactors dominates AECL's irradiation requirements, the new reactor concept is called the MAPLE Materials Testing Reactor (MAPLE-MTR).

Parametric physics and engineering studies are in progress on alternative MAPLE-MTR configurations to assess the capabilities for the following types of test facilities:

- fast-neutron sites, that accommodate materials-irradiation assemblies,
- small-diameter vertical fuel test loops that accommodate multi-element assemblies,
- large-diameter vertical fuel test loops, each able to hold one or more CANDU fuel bundles,
- horizontal test loops, each able to hold full-size CANDU fuel bundles or small-diameter multi-element assemblies, and
- horizontal beam tubes.

2. RESEARCH REACTOR IRRADIATION REQUIREMENTS

To achieve a consensus on the requirements for a new irradiation-research facility, AECL has established a committee that represents all user groups. As CANDU reactor support is the most important program for justifying a new AECL irradiation-research, particular attention has been devoted to examining its major components, namely, fuel technology, reactor materials technology and reactor safety research, and to identifying the aspects of the research that require a source of neutrons.

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1. CANDU (CANada Deuterium Uranium) is a registered trademark of AECL.

2.1 FUEL TECHNOLOGY

The fuel-technology program is a very crucial part of the AECL program because the CANDU fuel bundle is different from the fuel assemblies used in light-water power reactors. It consists of relatively short (0.5 m) lengths of fuel elements, clad in thin-walled collapsible sheaths and assembled with welded end plates. The fuel-technology program investigates the irradiation behaviour:

- of new (e.g., the 43-element CANFLEX bundle) and existing power reactor fuel designs, to improve and further qualify fuel for existing CANDU reactors under normal operating conditions and at extreme limits, and

- of new fuel designs for the next generation of CANDU reactors, including enriched and higher burnup fuels, low void and other passive safety designs, and improved fuel cycles.

2.2 REACTOR MATERIALS TECHNOLOGY

The reactor materials technology program is a AECL program because CANDU pressure tubes and calandria tubes are exposed to high neutron fluxes. The reactor materials technology program involves long-term research into:

- parametric studies to further develop and test predictive models for deformation, corrosion and fracture potential,

- end-of-life materials studies that allow the behavioural models to cover the full operational lifetime of the components,

- basic research to improve the fundamental understanding of in-reactor materials and

- development of improved materials and components.

2.3 REACTOR-SAFETY RESEARCH

The reactor-safety research program develops information to protect the investment in current CANDU plants and to ensure that future CANDU reactors can be licensed and operated safely. The program is directed at:

- improving the understanding of fuel and fuel-channel behaviour under the high-temperature conditions that characterize various loss-of-coolant accident and severe-fuel-damage scenarios,

- providing data to validate the computer codes and models for safety assessments and licensing of CANDU reactors in an anticipated environment of stricter regulatory requirements and an increased emphasis on passive safety design, and

- characterizing fission-product release, transport and deposition to fully quantify the source-term.

2.4 SPECIFIC EXPERIMENTAL REQUIREMENTS FOR CANDU SUPPORT

To achieve the foregoing objectives the irradiation-research facility must provide irradiation conditions that both match and exceed those found in a CANDU reactor. During this past year, a consensus has been reached on the specific experimental requirements described below.

2.4.1 Specific Fuel Technology Requirements

The peak linear heat ratings for current and future CANDU fuel range from 50 to 70 kW/m. Hence, there is a requirement to irradiate experimental fuel elements at these ratings. However, the enrichment is expected to vary from 0.71 wt% (^{235}U in total U) for the present once-through natural uranium fuel cycle to 1.9 wt% or more for low-void-reactivity (LVR) fuel that achieves an exit burnup of 21 GWd/MgU). Even without the extra enrichment required to support burnable poisons, the need for enriched CANDU fuels is inherent in the target of higher exit burnups (e.g., 1.2 wt% enrichment fuel for 21 GWd/MgU). CANDU fuel-irradiation requirements are summarized in Table 1.

As shown in Table 1, the corresponding fissile content of standard 13-mm elements varies proportionately from 7.5 g/m to ~20 g/m. Accordingly, CANDU fuel-irradiation facilities must cater to a range of fuel ratings per unit initial fissile content, from 2.5 to 9.3 kW/g ^{235}U (27-99 kW/m/wt% ^{235}U). For high-burnup advanced CANDU fuels, the principal range of interest is 2.5-5.5 kW/g fissile (27-58 kW/m/wt% ^{235}U).

TABLE 1

CANDU FUEL-IRRADIATION REQUIREMENTS
(standard 13-mm elements for 37-element bundles)

Reactor or Fuel Type	Enrichment (wt%)	Fissile Content (g/m)	Fuel Rating (kW/m)	Fuel Rating Per Unit Fissile (kW/m/wt%)	Fuel Rating Per Unit Fissile (kW/g fiss)
C-6 or OH	0.71	7.5	70	99	9.3
OH (Br/Da)	0.71	7.5	63	89	8.4
C-6	0.71	7.5	51	72	6.8
SEU*	1.2	12.7	70	58	5.5
	1.2	12.7	50	42	3.9
LVR	1.88	19.9	70	37	3.5
	1.88	19.9	50	27	2.5

* slightly enriched uranium

Through consulting with the users and analyzing their requirements, the following experimental specifications for irradiation-research facilities have been established:

1. Large-diameter loop facilities for development and prototype-demonstration of full-diameter CANDU fuel bundles:
   - capacity for at least four fuel bundles,

   - minimum flux length of 1.0 m for each test section,
   - representative CANDU conditions (flux, coolant temperature and coolant pressure), and
   - linear fuel-element ratings of 50 to 70 kW/m.

2. Small-diameter loop facilities for fuel-element testing:
   - single elements or partial-bundle multi-element assemblies,
   - representative CANDU conditions (flux, coolant temperature and coolant pressure),
   - capacity for four test sections,
   - linear fuel-element ratings of 50 to 70 kW/m, and
   - capability to vary coolant conditions.

3. Diagnostic capability using:
   - in-pool beam tube for neutron radiography of irradiation fuel (thermal-neutron flux of ~0.7×10^{18} $n{\bullet}m^{-2}{\bullet}s^{-1}$), and
   - external beam tube for neutron radiography (thermal-neutron flux of ~2×10^{18} $n{\bullet}m^{-2}{\bullet}s^{-1}$).

2.4.2 Specific Reactor Materials Technology Requirements

Linear heat ratings of 50 to 70 kW/m in the CANDU fuel corresponds to fast-neutron ($E \geq 1$ MeV) fluxes at the pressure tube of 0.3 to 0.7×10^{18} $n{\bullet}m^{-2}{\bullet}s^{-1}$. The specific requirements of the reactor materials technology program are related to the conditions required to represent the CANDU reactor and the conditions that allow accelerated ageing of CANDU fuel-channel components.

In consultation with the users, the following experimental specifications have been established:

1. Facilities to test full-diameter CANDU fuel-channel sections:
   - capacity for four fuel-channel sections and
   - representative CANDU conditions (flux, coolant temperature and coolant pressure).

2. Deformation and fracture facilities for irradiating small specimens in three fast-neutron ($E_n \geq 1$ MeV) flux environments:
   - medium 0.7×10^{18} $n{\bullet}m^{-2}{\bullet}s^{-1}$ (4-5 capsules),
   - high 1.8×10^{18} $n{\bullet}m^{-2}{\bullet}s^{-1}$ (2 capsules), and
   - ultra high 3.0×10^{18} $n{\bullet}m^{-2}{\bullet}s^{-1}$ (2-3 capsules).

3. Corrosion-testing loops for irradiating small specimens:
   - fast-neutron fluxes of ~0.7 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$,
   - stainless-steel loops with standard or variable coolant chemistry, and
   - recirculating gas loop.

4. Diagnostic capability using:
   - external beam tube for neutron radiography (thermal-neutron flux of ~2 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$), and
   - beam tube access for three instruments: one for residual strain determination, one for texture determination and one for chemical phase and annealing studies (thermal-neutron flux of ~3 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$).

2.4.3 Specific Reactor-Safety Research Requirements

In consultation with the users, the following experimental specifications have been established:

1. Test section to handle fuel elements under accident conditions:
   - horizontal orientation to match CANDU fuel-channel orientation,
   - representative flux, coolant temperature and coolant pressure conditions,
   - linear fuel-element ratings of 50 to 70 kW/m,
   - single elements or partial-bundle multi-element assemblies with instrumentation, and
   - high-integrity loop system to study accident conditions.

2. Diagnostic capability using:
   - in-pool beam tube for neutron radiography of irradiation fuel (thermal-neutron flux of ~0.7 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$), and
   - external beam tube for neutron radiography (thermal-neutron flux of ~2 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$).

2.5 NEUTRON BEAM REQUIREMENTS

The AECL condensed matter science program provides a materials analysis capability in support of CANDU development and participates in AECL's national laboratory role. At present, the study team has concentrated on the requirements to support CANDU development. Accordingly, efforts will be made to match the beam-tube capabilities (i.e., thermal-neutron fluxes of ~2.0 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$) of the NRU reactor in any new reactor and possibly to allow a cold neutron source to be added in the future.

3. MAPLE MATERIALS TEST REACTOR DESCRIPTIONS

Several configurations (P0 - P6) of the MAPLE-MTR concept have been studied to explore the range of capabilities that can be provided. The features included in each of the seven configurations (Figure 1) are summarized in Table 1. All MAPLE-MTR configurations were based on the following basic features:

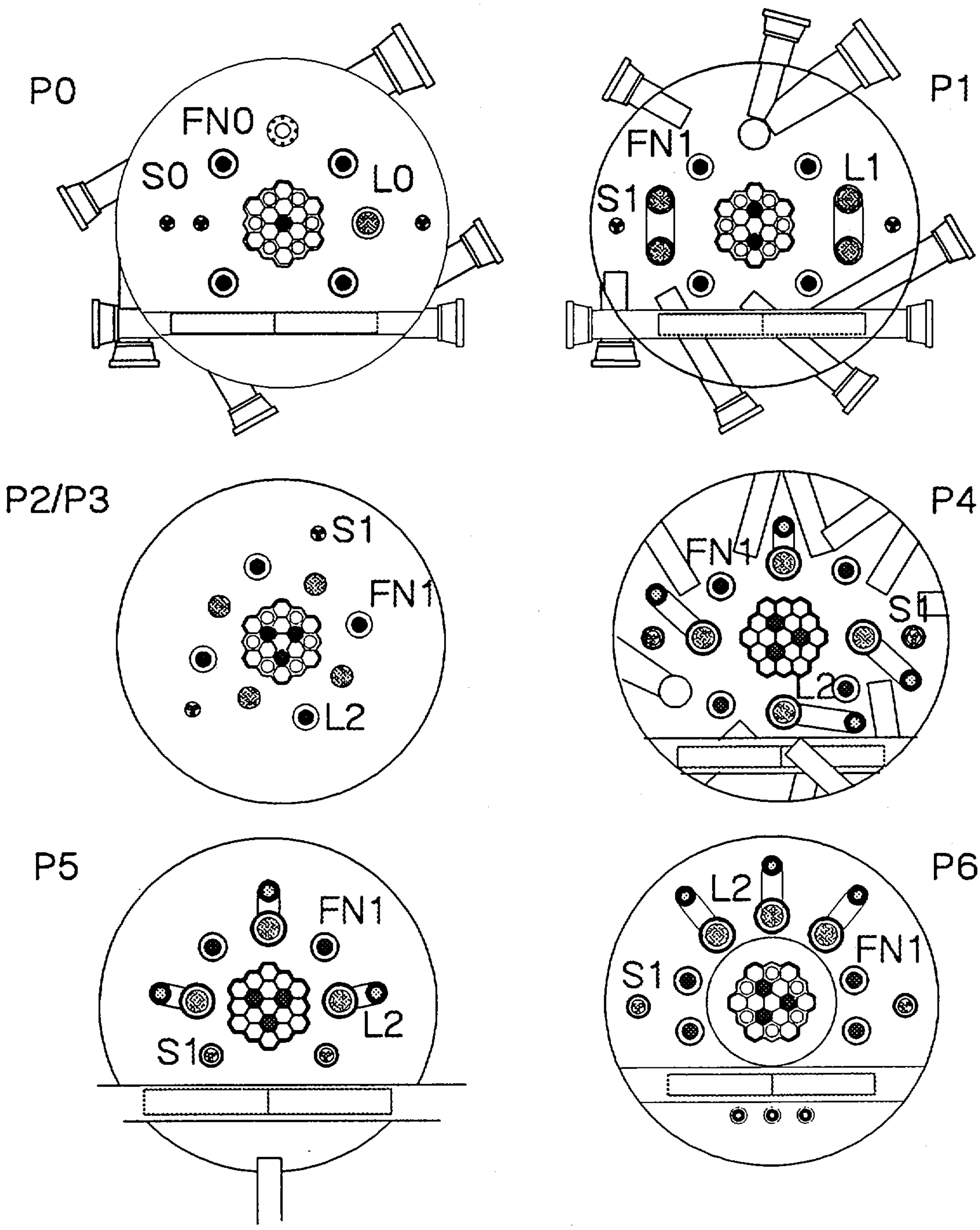

Figure 1: MAPLE-MTR Configurations

TABLE 2

SUMMARY OF FEATURES IN MAPLE-MTR CONFIGURATIONS

FEATURE	CONFIGURATION						
	P0	P1	P2	P3	P4	P5	P6
CORE							
# HEX. FUEL	12	11	10	10	16	16	10
# CYL. FUEL	6	6	6	6	0	6	6
# IRRAD. SITES	1	2	3	3	3	3	3
POWER (MW)	15	15	15	20-25	20-25	21	15
FN-RODS							
TYPE	FN0	FN1	FN1	FN1	FN1	FN1	FN1
NUMBER	4	4	4	4	4	2	4
LOOPS							
# LARGE DIA./TYPE	1/L0	4/L1	4/L2	4/L2	4/L2	3/L2	3/L2
# SMALL DIA./TYPE	3/S0	2/S1	2/S1	2/S1	2/S1	2/S1	2/S1
# HORIZ.	1	1	0	0	1	1	1
BEAM TUBES	5	7	0	0	10	1	0
COLD SOURCE	1	1	0	0	1	0	0

- hexagonal 36-element driver fuel assemblies,
- cylindrical 18-element fuel assemblies for the control and shutdown sites,
- hafnium absorbers for reactivity control, and
- a D_2O reflector with a dump system to provide a diverse shutdown mechanism.

The P0 to P2 configurations examined the capabilities to provide the desired fast-neutron fluxes and fuel-irradiation conditions for several CANDU fuel elements. The P3 configuration focussed on increasing the fast-neutron flux and the power output from the fuel test loops by using an alternative driver fuel to achieve higher power from the core. The P4 to P6 configurations focussed on the performance of experimental facilities for full-diameter CANDU fuel bundles and for safety-related tests. The P3 to P5 configurations require some departures from the basic core design and imply further development work. The P6 configuration features the basic core design described above.

Two versions of the fast-neutron (FN) rods were examined as part of the study:

- FN0 consisted of 42 MAPLE-type fuel elements with two rings, and a central irradiation space of 60 mm inner diameter, and
- FN1 consisted of 58 MAPLE-type fuel elements with two rings, and a central irradiation space of 75 mm inner diameter for compatibility with the materials irradiation rigs for the core.

Two versions of the small-diameter fuel test loops were examined as part of the study:

- a re-entrant test section (S0) to hold from one to four elements and
- a re-entrant test section (S1) to hold from one to seven elements.

Three versions of the large-diameter fuel test loops were examined as part of the study:

- a re-entrant test section (L0) to hold one CANDU fuel bundle,
- a U-shaped test section (L1) with one or two CANDU bundles in each leg of the 'U', and
- a once through test section (L2) with one or two CANDU bundles.

For the re-entrant test section, the coolant flows down an outer annulus and up through the CANDU fuel bundle. For the U-shaped test section, the coolant flows down through one CANDU bundle and up through the second. For the once-through test section, the coolant flows down through a small diameter pipe and up through the CANDU fuel bundle(s). The CANDU bundles for the vertical test loops differ from the actual CANDU bundles in that the centre fuel element is replaced with a solid support rod. Hence the test bundles have 36 CANDU fuel elements arranged in three rings.

4. RESULTS OF PHYSICS CALCULATIONS

The physics calculations for the early (P0 to P2) MAPLE-MTR configurations predict that perturbed fast-neutron fluxes of at least 1.4 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$ are achieved at a core power output of 15 MW. The calculations also showed that the minimum requirements for fast-neutron fluxes for accelerated-ageing investigations can be met in the MAPLE-MTR core.

For the early MAPLE-MTR configurations, perturbed fast-neutron fluxes of 0.4-0.6 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$ can be achieved in the FN-sites with a core power output of 15 MW. These fast-neutron fluxes match normal operating conditions in CANDU reactors.

For the P0 MAPLE-MTR configuration, the S0 small-diameter fuel test loop provides:

- peak linear ratings of 67 kW/m in each of four natural UO_2 fuel elements at a distance of 100 mm from the core, and
- peak linear ratings of 47 kW/m in each of four natural UO_2 fuel elements at a distance of 270 mm from the core.

A parametric assessment of the small-diameter fuel test loop has produced the results shown in Figure 2 for the S1 small-diameter fuel test loop. These calculations were performed with the P6 MAPLE-MTR configuration with a core power output of 15 MW. The linear element ratings in a typical CANDU bundle are also shown in Figure 2 for comparison. These results show that this type of small-diameter fuel test loop can be used to simulate the element ratings for

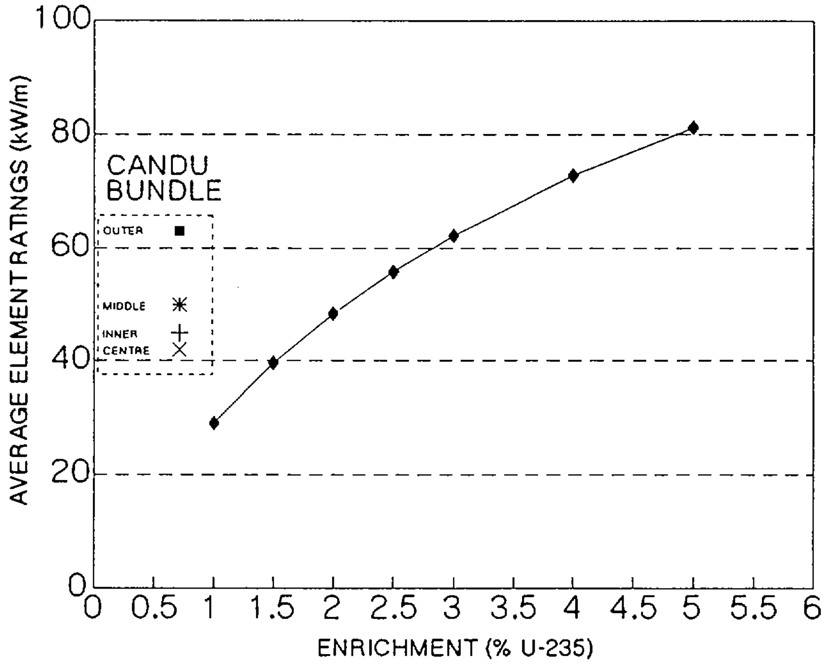

Figure 2: Average CANDU Element Ratings as a Function of ^{235}U Enrichment in a Small-Diameter Test Loop with Six CANDU Elements

the different rings of elements in a CANDU bundle by adjusting the enrichment in the test assembly.

A parametric assessment of the large-diameter fuel test loop has produced the results shown in Figure 3 for the L2 large-diameter fuel test loop. These calculations were performed with the P6 MAPLE-MTR configuration with a core power output of 15 MW. The linear element ratings in a typical CANDU bundle are also shown in Figure 3 for comparison. It is expected that this type of large-diameter fuel test loop can be used to simulate a wide range of conditions for the CANDU bundle by suitable adjustment of the enrichment.

The fast-neutron fluxes within the CANDU fuel bundle are shown in Figure 4. For comparison, the fast-neutron flux in the centre of the hottest channel, the outside of the hottest channel and the outside of an average channel in a BRUCE-A CANDU unit are also shown in Figure 4. The results in Figure 4 indicates that the test bundle can be adjusted either to match the range of fast-neutron flux conditions in the CANDU reactor by suitable adjustment of the enrichment or to exceed the fast-neutron flux conditions and accelerate damage effects for the cladding.

These parametric assessments help define the capabilities that can be included in a new irradiation facility based on the MAPLE-MTR concept. Further assessments are in progress to understand the trade-offs among different types of experimental facilities as well as to understand the mix of irradiation capabilities required.

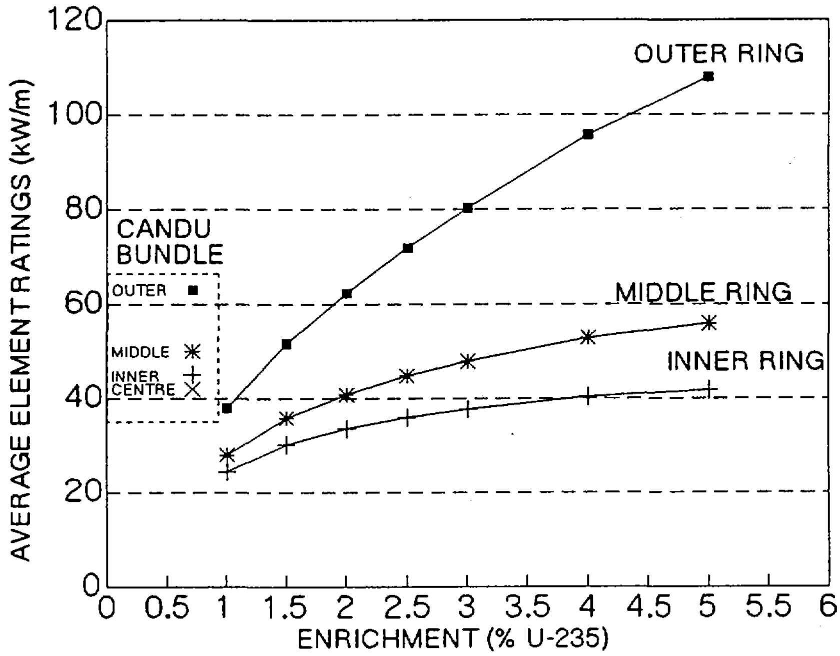

Figure 3: Average CANDU Element Ratings as a Function of ^{235}U Enrichment in a Large-Diameter Test Loop with a 36-Element CANDU Bundle

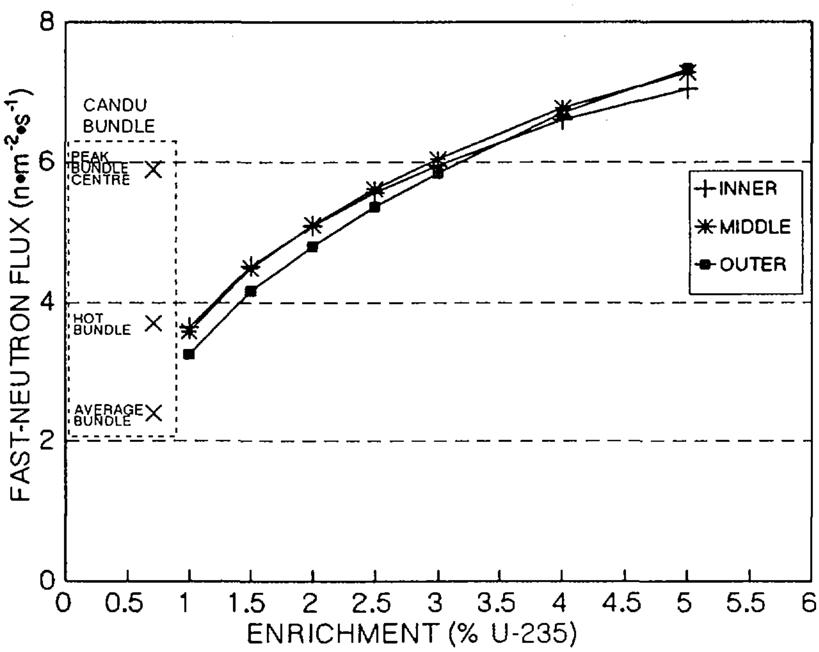

Figure 4: Fast-Neutron Fluxes in a CANDU Bundle as a Function of ^{235}U Enrichment

5. SUMMARY

AECL is at an early stage in its evaluation of options for future irradiation facilities. During the past year the irradiation requirements for the CANDU support research programs have been reviewed and a consensus on these requirements has been achieved. Work is currently in progress to interpret these irradiation requirements to provide detailed technical performance specifications for experimental facilities.

Computer simulations of experimental facilities needed to satisfy various irradiation requirements are in progress. The initial calculations have identified how individual experimental facilities could perform in a MAPLE-MTR. Further analyses of fuel test loops and materials test rigs are under way to characterize interactions among the experimental facilities. As part of the options assessment, work has also been initiated to identify what irradiation capabilities can be provided in existing research reactors to cover near-term requirements.

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REFERENCES

1. Lee, A.G., Lidstone, R.F. and Donnelly, J.V., "Planning a New Research Reactor For AECL: The MAPLE-MTR Concept," Proceedings of the 2nd meeting of the International Group on Research Reactors, Saclay, France, 1992 May 18 and 19.

2. Lee, A.G., Bishop, W.E. and Heeds, W., "Safety Features Of The MAPLE-X10 Design," Proceedings of The Safety, Status And Future Of Non-Commercial Reactors And Irradiation Facilities, Boise, Idaho, 1990 September 30 to October 4.